Analysis of Self-Excited Induction Generator under Balanced or Unbalanced Conditions

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Abstract: **This paper presents mathematical models for various generator-load configurations that accurately determine the conditions for self-excitation and performance characteristics of an isolated , three-phase, self-excited induction generator operating under balanced or unbalanced conditions .These models are derived using symmetrical component theory along with the generator sequence equivalent circuits. Using this technique a 4.5kW, 400/440V, four poles, three-phase induction motor operated as a SEIG is analysed under different balanced or unbalanced configuration.**

Key Words**: Induction generator, self-excited, steady state analysis, unbalanced.**

1. INTRODUCTION

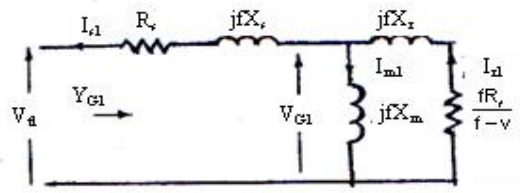
The self-excited induction generator (SEIG) has attracted considerable recent attention due to its applicability as a stand-alone generator using different conventional and non-conventional energy resources with its advantage over the conventional synchronous generator. .Due to the research of renewable energy resources and isolated power systems, the SEIG become one of the most important renewable sources in developing countries [1-4].Besides application as a generator, the principle of self-excitation can also be used for dynamic braking of three phase induction motors [5]. Many papers have discussed analysis of three-phase balanced operation of isolated and parallel operated self-excited induction generator [6-10]. However, the unbalanced operations of such generators have been given comparatively little attention. This mode of operation may sometimes be of interest for various small-scale applications where either balanced conditions are not necessary or difficult to achieve. Certain specific cases of unbalanced conditions in a SEIG have been discussed in several papers [4& 9-11]. However, no general method of analysis for the unbalanced mode of operation of the SEIG is available. For single-phase system, the single – phase SEIG could be used with advantage. However, when the power requirements of the remote area are higher than the normal available ratings of single-phase induction machine have to be constructed to tailor made needs and this may prove to be expensive .As an alternative, the three-phase SEIG can be used as a single-phase generator [11&12]. Used thus, the system may work out to be lesser in cost than the specially designed single-phase SEIG of equivalent capacity. This paper presents general mathematical models that determine the conditions of self-excitation and performance characteristics of an isolated, three-phase SEIG under balanced or unbalanced excitation [13].

II. PROPOSED MODELS

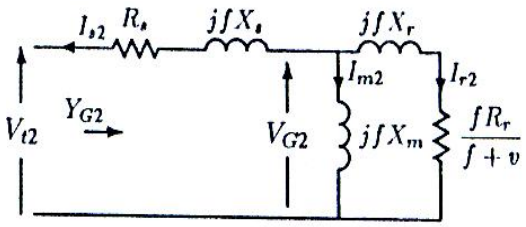
Consider a 3-ϕ induction machine connected to a 3-ϕ network consisting of excitation capacitors with or without a parallel load. The machine may have star or delta connected windings. Similarly, the network may be connected in either star or delta. Further, this network may be either balanced or unbalanced. For a given configuration (star or delta) of the generator & the load, the method of symmetrical components can be used to analyze the performance of the system.

Sequence equivalent circuits

The positive and negative sequence equivalent network of a SEIG [14] is shown below in fig. (1)



(a) Positive Sequence



(b) Negative Sequence

Figure 1 Sequence equivalent circuits of a SEIG

A Delta Connected Generator

Let us assume that a 3-ϕ delta connected induction machine is connected across a 3-ϕ delta connected network having admittances Y_{ab}, Y_{bc} & Y_{ca} as shown in fig (2). Each branch of the delta network may consist of an excitation capacitor in parallel with a general load as shown in fig (3.3) for a-b branch.

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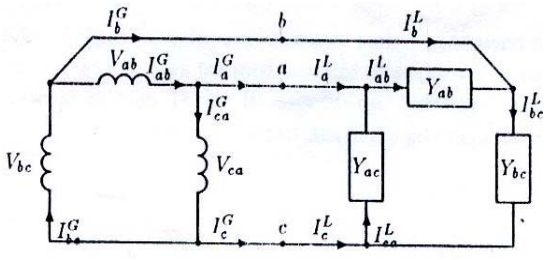

Figure2. Delta connection of a SEIG & load-excitation capacitors

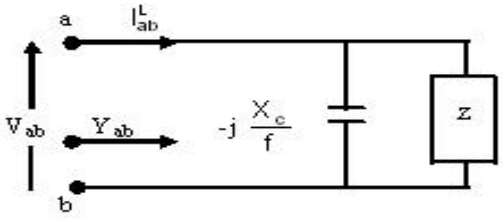

Figure3. Equivalent circuits of a-b branch

$$Z = R + jf\,X \text{ for R-L load}$$

$$Z = R - \frac{jX}{f} \text{ for R-C load}$$

The method of symmetrical components can be used to resolve the unbalanced admittances of the network of fig (2) into a set of sequence admittances as follows:

$$\begin{pmatrix} Y_o \\ Y_1 \\ Y_2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} Y_{ab} \\ Y_{bc} \\ Y_{ca} \end{pmatrix} \quad (1)$$

In fig (2), the phase currents I_{ab}^L, I_{bc}^L & I_{ca}^L can be related to the phase voltages and admittances. By using symmetrical components transformations, these phase currents can be resolved into their sequence components as

$$\begin{pmatrix} I_{abo}^L \\ I_{ab\,1}^L \\ I_{ab\,2}^L \end{pmatrix} = \begin{pmatrix} Y_0 & Y_2 & Y_1 \\ Y_1 & Y_0 & Y_2 \\ Y_2 & Y_1 & Y_0 \end{pmatrix}\begin{pmatrix} V_{abo} \\ v_{ab\,1} \\ V_{ab\,2} \end{pmatrix} \quad (2)$$

As in a delta connected passive network, there is no zero sequence voltage i.e.V_{abo} = 0. Thus, the positive and negative sequence components of the line & the phase load currents are related by

$$Ia_1^L = (1-a)\, I_{ab1} \quad (3)$$

$$Ia_2^L = (1-a^2)\, I_{ab\,2} \quad (4)$$

From (2)

$$I_{ab1} = Y_0V_{ab1} + Y_2V_{ab2}, \quad I_{ab2} = Y_1V_{ab1} + Y_0V_{ab2}$$

Therefore,

$$I_{a\,1}^L = (1-a)(Y_0V_{ab\,1} + Y_2V_{ab\,2}) \quad (5)$$

$$I_{a\,2}^L = (1-a^2)(Y_1V_{ab\,1} + Y_0V_{ab\,2}) \quad (6)$$

From the sequence networks of fig (1), the generator sequence currents are given by

$$I_{s1} = -Y_{G1}V_{t1} \text{ and } I_{s2} = -Y_{G2}V_{t2}$$

Since in fig (2), the generator is Δ-connected, the positive and negative sequence components of the generator line currents are given as:

$$I_{a\,1}^G = (1-a)\,Is_1 = -(1-a)Y_{G1}V_{t1} \quad (7)$$

$$I_{a\,2}^G = (1-a^2)\,Is_2 = -(1-a^2)Y_{G\,2}V_{t2} \quad (8)$$

From terminal conditions,

$$I_{a\,1}^L = I_{a\,1}^G \;\&\; I_{a\,2}^L = I_{a\,2}^G \quad (9)$$

Moreover, for the Δ-connected generator, the phase & the line voltages are equal

$$\therefore V_{t1} = V_{ab1} \;\&\; V_{t2} = V_{ab2} \quad (10)$$

From (9) & (10)

$$(Y_0 + Y_{G1})\,V_{t1} = -Y_2\,V_{t2} \quad (11)$$

$$Y_1\,Vt_1 = -(Y_{G2} + Y_0)\,Vt_2 \quad (12)$$

After dividing (11) by (12), we get

$$(Y_{G1} + Y_0)(Y_{G2} + Y_0) - Y_1\,Y_2 = 0 \quad (13)$$

This is the equation for Δ - connected generator and Δ - connected network.

B Star Connected Generator with No Neutral Connection

Consider a 3-ϕ Y-connected induction machine connected across a 3-ϕ Y-connected network as shown below

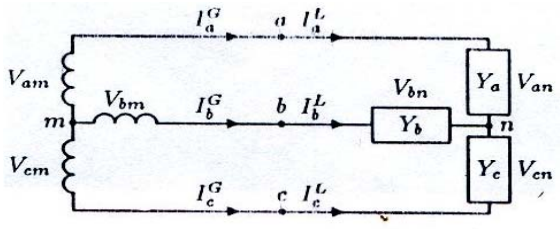

Figure4. Star connection of a SEIG and load-excitation capacitors.

Let Y_0, Y_1, Y_2 represent the sequence admittance components of Y_a, Y_b & Y_c. The current I_a^L, I_b^L and I_c^L can be related to the load phase voltages and admittances. Using symmetrical components theory, these currents can be resolved into their sequence components as follows:

Since, for the circuit of fig. (4), $I_{a\,0}^L = 0$,

$$V_{an0} = (Y_2\,V_{an1} + Y_1\,V_{an2})/Y_0 \quad (14)$$

Consequently,

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$$I^{L}_{a1} = \left(Y_0 - \frac{Y_1 Y_2}{Y_0} \right) V_{an1} + \left(Y_2 - \frac{Y_1^2}{Y_0} \right) V_{an2} \quad (15)$$

$$I^{L}_{a2} = \left(Y_1 - \frac{Y_2^2}{Y_0} \right) V_{an1} + \left(Y_0 - \frac{Y_1 Y_2}{Y_0} \right) V_{an2} \quad (16)$$

However, the generator sequence currents are given as

$$I^{G}_{a1} = - Y_{G1} V_{am1} \quad (17)$$

$$I^{G}_{a2} = - Y_{G2} V_{am2} \quad (18)$$

It is noted that the generator and the load phase voltages may not be equal under unbalanced conditions. However, the generator and the load line voltages are equal regardless of the degree of unbalance.

Sequence components of the phase and line voltages of the generator and load are related as

$$V_{ab1} = (1-a^2) V_{an1} = (1-a^2) V_{am1} \quad (19)$$

$$V_{ab2} = (1-a) V_{an2} = (1-a) V_{am2} \quad (20)$$

Hence $V_{an1} = V_{am1}$ & $V_{an2} = V_{am2}$

Also, from fig (4)

$$I^{G}_{a1} = I^{L}_{a1}, \; I^{G}_{a2} = I^{L}_{a2}$$

Therefore,

$$\left(Y_{G1} + Y_0 - \frac{Y_1 Y_2}{Y_0} \right) V_{an1} = - \left(Y_2 - \frac{Y_1^2}{Y_0} \right) V_{an2} \quad (21)$$

$$\left(Y_1 - \frac{Y_2^2}{Y_0} \right) V_{an1} = - \left(Y_{G2} + Y_0 - \frac{Y_1 Y_2}{Y_0} \right) V_{an2} \quad (22)$$

Dividing (21) by (22)

$$\left(Y_{G1} + Y_0 - \frac{Y_1 Y_2}{Y_0} \right) \left(Y_{G2} + Y_0 - \frac{Y_1 Y_2}{Y_0} \right) - \left(Y_1 - \frac{Y_2^2}{Y_0} \right) \left(Y_2 - \frac{Y_1^2}{Y_0} \right) = 0 \quad (23)$$

This is the equation for Y-connected generator & Y-connected network.

C Special Cases

The above models are general and can be used for balanced and for any unbalanced conditions. In this paper, the model for a Y-connected generator will be applied for some selected cases. However similar analysis may also be carried out for Δ - connected generator and Δ - connected network.

Balanced Network - Assume that, in fig (4), the network is balanced and $Y_a = Y_b = Y_c = Y$ from (1) $Y_0 = Y$ & $Y_1 = Y_2 = 0$.Therefore, from (23)

$$(Y_{G1} + Y)(Y_{G2} + Y) = 0 \quad (24)$$

Which implies that either

$$Y_{G1} + Y = 0 \quad (25)$$

Or

$$Y_{G2} + Y = 0 \quad (26)$$

It is noted that (25) also offers the feasible solution which represents the balanced operation of SEIG [2, 3].

Two phases open - Suppose that there is only one excitation capacitor is parallel with a load i.e. $Y_a = Y$ and $Y_b = Y_c = 0$ .Therefore $Y_0 = Y_1 = Y_2 = Y/3$. Hence (21) reduces to

$$Y_{G1} Y_{G2} = 0 \quad (27)$$

The above equation can be represented by connecting positive and negative sequence equivalent circuit in parallel.

III Method of Solution

Equation (13) & (23) represent the conditions that must be satisfied for the self-excitation of the induction machine corresponding to various generator & load configurations as discussed above. Each of these equations is complex and non-linear which can be expressed as two simultaneous real, nonlinear equations with two unknowns. Such equations can be solved using any suitable technique (Symbolic Mathematics in MATLAB). If the values of the machine parameters, its speed (or frequency), excitation capacitance as well as load impedances are given, the two equations can be solved for the magnetizing reactance and frequency (or speed). On the other hand, if the interest is to find the range of terminal capacitances to sustain self-excitation, the two equations can be solved for the frequency (or speed) and these capacitances by specifying the machine parameters, its speed (or frequency), load impedances and the maximum magnetizing reactance, X_{max} .Consequently, $X_m = X_{max}$ represents the critical conditions for self-excitation. Once X_m, f and v are known, the complete performance of the generator can be evaluated provided the machine magnetizing characteristics are given

IV Experimental Results And Discussion

Fig (5) and (6) respectively show the variation of the terminal voltage with rotor speed (rpm) for different values of capacitance (i.e. 20, 45, 80, 108μF) when the test machine was under no-load and star connected for balanced and unbalanced excitation (line excitation). It is noted that the no-load terminal voltage increases with speed for both balanced and unbalanced excitation. The terminal voltage is the highest at no-load and decreases as the machine is loaded with resistive load (balanced load). It is important to point out that the terminal voltage is sensitive to both C and the machine load. Similar sets of terminal voltage versus speed patterns for different values of C are observed in literature also [8, 12 and 13]. Fig (7) shows the variation of stator current with rotor speed for different values of excitation capacitance (i .e 20, 45, 80, 108 μF) when the test machine was under no load and star connected for balanced excitation. It is noted that no load stator current increases with speed. Fig (8) shows that when the machine

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is loaded with R=450Ω, the stator current decreases with increased load. It is clear from this figure that the value of C has to be selected carefully because certain values of C can result into excessive high value of V_t and stator current which can cause over heating and may damage the machine insulation. Similar sets of stator current versus speed patterns for different values of C are observed in literature also [8, 12 and 13]. Fig (9) and (10) shows the variation of frequency with speed under no-load for C=80μF and 108μF. It is noted that the difference in C doesn't affect the frequency and depends mainly on speed. When the SEIG is loaded then both speed and frequency decreases.

CONCLUSIONS

The performance characteristics of an isolated, three-phase, self-excited connected induction generator can be predicted with accuracy under balanced or unbalanced conditions. In general the performance characteristics are strongly influenced by the value of C. Because the induction generator is isolated, its stator frequency is free to vary with the rotor speed and the operating slip remains small. This in turn results in high efficiency. Due to their simplicity, ruggedness and low cost of construction, squirrel-cage induction machine is a relatively inexpensive alternative to ac generation using wind power for voltage and frequency insensitive loads.

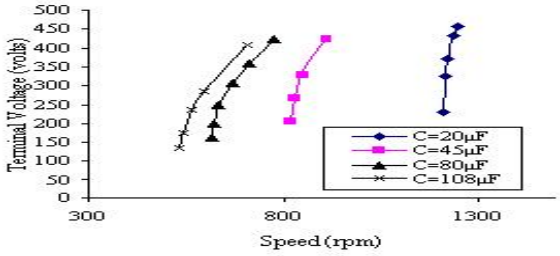

Figure 5. Variation of terminal voltage with speed when the test machine was under no load and star connected for unbalanced excitation

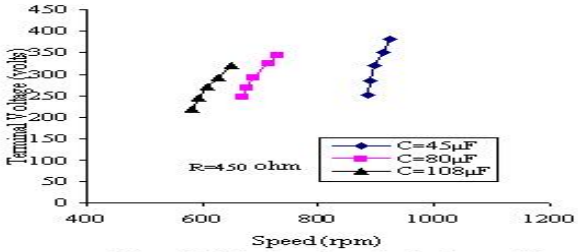

Figure 6. Variation of terminal voltage with speed when the test machine was loaded and star connected

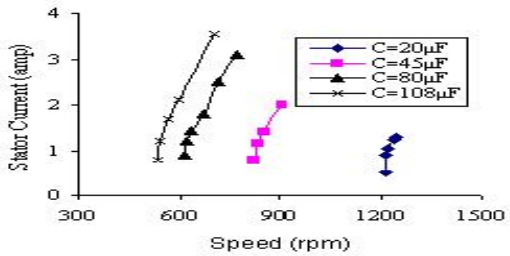

Figure 7. Variation of stator current with speed when the test machine was under no load

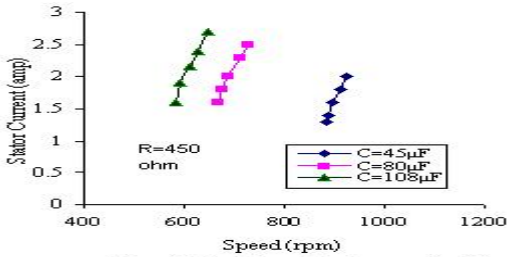

Figure 8. Variation of stator current with speed when the test machine was loaded and star connected

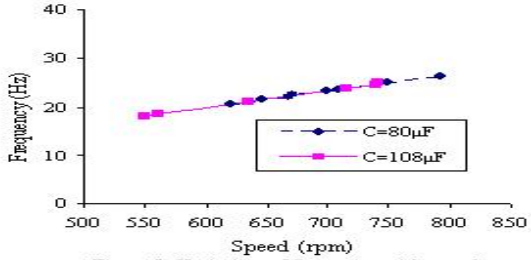

Figure 9. Variation of frequency with speed under no load

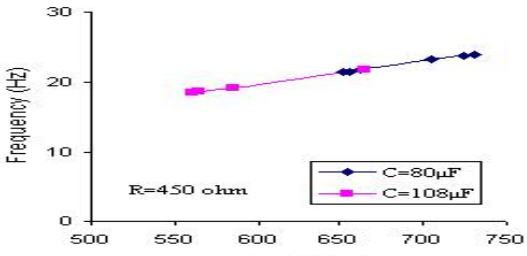

Figure 10. Variation of frequency with speed under load

LIST OF SYMBOLS

f , v	=	Frequency and speed
fb	=	Base frequency
Z_b	=	Base impedance
R_s, R_r, R	=	Stator, Rotor (referred to stator) and load resistance respectively
X_s, X_r, X_m , X_c	=	Stator , Rotor (referred to stator) magnetizing and excitation reactance at base frequency respectively

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X, X_{max} = Load and maximum magnetizing reactance at base frequency respectively

C_{min} , C_{max} = Minimum and maximum values of excitation capacitance (μf)

I_{s1}, I_{r1}, I_{m1} = Positive sequence stator, rotor (referred to stator) and magnetizing currents resp.

I_{s2}, I_{r2}, I_{m2} = Negative sequence stator, rotor (referred to stator) and magnetizing currents resp.

Vt_1, Vg_1 = Positive sequence per phase generator terminal and air-gap voltages resp.

Vt_2, Vg_2 = Negative sequence per phase generator terminal and air-gap voltage resp.

Y_{G1}, Y_{G2} = Positive and negative sequence per phase generator terminal admittances at base frequency resp

a, a^2 = $e^{j\frac{2\pi}{3}}$ and $e^{-j\frac{2\pi}{3}}$ resp.

All parameters except C_{min} and C_{max} are in p.u

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APPENDIX A

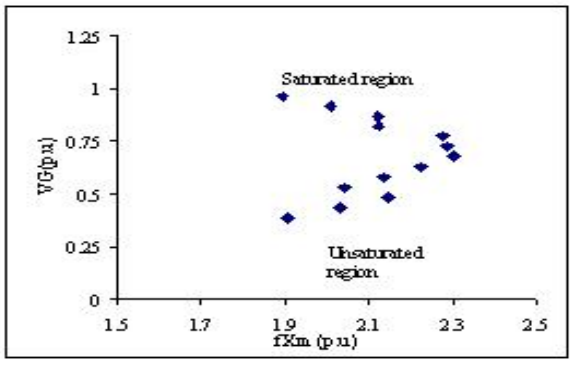
Specification and parameters of Machine

3-ϕ , 4-pole , 50Hz 400/440V, 8.5A, 50Hz, 4.5/6 kW/hp, 1440 rpm, star connected stator winding induction machine R_S = 0.068993, R_r = 0.012492**,** X_s = X_r = 0.074575

Air-gap Voltage

$V_G = 1.895\text{-}0.492\ fX_m$ for $1.8936 \leq fX_m 2.27393$

$= 0$ for $fX_m < 1.8936$



Fiigure11. Variation of V_G with fX_m – a linear approximation

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